



SUMMARY OF WOOD-FRAMED EXTERIOR WALL PERFORMANCE STUDY

In 1998 members of Seattle's Construction Codes advisory board (CCAB) and the Seattle Department of Design, Construction and Land Use (DCLU) began looking into the well-known problem of moisture damage in newer multifamily buildings in the Seattle area (see Attachment 1). One outcome of their efforts has been a computer simulation study performed by the Oakridge National Laboratories (ORNL).

Researchers at the ORNL have completed computer simulations of the hygrothermal performance (see Attachment 2) of typical wood-frame exterior wall systems used in the Seattle area and reported their findings in a report entitled *Building Enclosure Hygrothermal Performance Study*. Hygrothermal performance is the measure of the combined heat, air and moisture flows within a wall system based on the material property characteristics of each component within the wall, and the interior and exterior environmental conditions to which the wall will be exposed. The study seeks to expand the knowledge base for regional builders, owners, and officials concerned about significant moisture damage encountered in recently constructed multifamily structures. The study was requested by members of the Seattle CCAB, DCLU, and the Washington State University Cooperative Extension Energy Program.

Exterior Wall Performance Study

For the study, components of the walls were varied to create 33 typical wood-frame walls. In addition, a few examples of walls typically constructed before 1984 were included to determine if there were significant differences in the predicted hygrothermal performance of "older" walls versus "newer" walls. The computer model predicted the moisture content of each component in the wall, as well as the moisture content of the whole wall system based on the material property characteristics of each component subjected to hourly exterior weather data for Seattle (temperature, relative humidity, solar radiation, wind driven rain, wind speed, and wind direction), hourly interior conditions (temperature, pressures and relative humidity), and a calculated rate of moisture intrusion (leak) into the wall system during each rain event.

Because the mere presence of moisture does not necessarily condemn a wall to failure, the results of the computer modeling were fed into a risk assessment model that calculated a "mold growth index" to determine if the walls remained wet and warm long enough to induce mold growth. The walls were then ranked according to their relative performance on a mold growth scale, with walls showing little or no predicted mold growth scoring lower on the scale, and walls with severe predicted mold growth scoring higher. All walls were modeled assuming good construction and that a small percentage of the wind-driven rain striking the surface of the wall penetrated behind the exterior cladding and weather resistive barrier.

A load based analysis, including loads due to the effect of mechanical ventilation and high interior relative humidity, were included in the modeling in order to better understand the importance of these factors. The effect of material selection on wall performance was tested by modeling similar walls with different components serving the same function, such as plywood sheathing versus oriented strand board sheathing, or concealed barrier claddings versus ventilated claddings. Walls with different levels of insulation and vapor retarder strategies were modeled to assess the impact of Energy Code changes on exterior wall performance.

Next Phases of the Study

The simulations mark Phase I of a larger study and provide a preliminary assessment of typical walls used in multifamily construction in Seattle, as well as newer innovative wall systems. Phase II will involve the construction of a full-scale test facility to test wall assemblies, further develop the database of construction materials properties, and develop a database of properties associated with various construction practices. Phase III will seek ways to improve water management capabilities of wall systems through both field work and computer modeling, as well as develop a model building guide for the Puget Sound region. The completed version of Phase I is scheduled to be published in August 2002 and will be made available by DCLU both online and in hard copy.

General Observations

The study considered both external and internal sources of moisture, but focused on problems caused by exterior moisture intrusion, typically leaks associated with wind-driven rain. Surveys done in Vancouver, British Columbia and Seattle indicated that exterior leaks are the main source of moisture problems in newer buildings.

Using a systems approach, the performance of a building envelope can be optimized based on considerations of the exterior and interior environments, the vapor permeability of components, the number of weather resistive barrier layers, and the moisture storage ability of wall components. This systems approach is based on understanding the hygrothermal performance of each element in a wall and the role that element plays in the overall performance of a building envelope.

Findings from the study include:

- the importance of selecting building materials that allow walls to dry to both the interior and the exterior, provided interior conditions allow for drying to the inside;
- the importance of controlling interior relative humidity;
- and the apparent beneficial performance of ventilated “rain screen” wall assemblies.

Additional value of this innovative research was gained through the first ever use of a new quantitative engineering assessment tool, the “Mold Growth Index”, to compare the relative performance of the wall systems studied.

The simulations assume good construction, which is represented by selection of a low rate of exterior moisture intrusion (leakage) in the modeling simulations.

Consequently, the simulations do not directly address the issues of poor design or workmanship. Other factors that were not modeled by the simulations may affect the performance of exterior walls. Some of these factors are:

- introduction of new building materials with unknown hygrothermal characteristics;
- high initial moisture content due to materials being left exposed during construction;
- improper installation of flashing and weather resistive barriers;
- attempting to “dry the building out” by raising indoor temperatures above normal before occupancy;
- fragmentation of development and construction responsibilities; and
- complexity of coordinating subcontractors

Although not part of the simulations, many designers, builders and building officials agree that the two most important steps that can be taken to improve the quality and durability of wood-frame exterior walls are as follows:

- Develop design drawings, installation details, and building instructions that clearly address the goal of managing the flow of moisture on, in, and through the building envelope.
- Train and instruct those responsible for carrying out construction in the appropriate practices for executing the design details set forth in the project drawings.

The study was conducted by Achilles Karagiozis of the The Building Technology Center at Oak Ridge National Laboratory, in partnership with the City of Seattle’s Dept. of Design, Construction and Land Use, Construction Codes Advisory Board and the Washington State University Cooperative Extension Energy Program. It was in large part funded under the auspices of ORNL’s State Partnerships Program, which, among other goals, seeks to use ORNL’s technical capabilities and resources to assist state and local energy agencies to apply developing sustainable technologies.

Specific Observations

- **Managing Water Penetration:** Building envelopes should be designed to manage the flow of incidental moisture. It is especially important to reduce the amount of water entering the wall where adjoining building envelope components meet and where there are envelope penetrations such as windows, vents, doors, and decks.
- **Choice of Weather Resistive Barrier (WRB) or “building paper”:** Proper installation of weather resistive barriers and integration with flashing is one of the most important factors in the successful performance of exterior walls. Two layers of WRB (one layer installed over the other) behind the exterior cladding was shown to provide better drainage control than one layer.
- **Ventilated Cladding vs. Concealed Barrier Cladding:** The computer modeling showed that in the Seattle climate, “ventilated claddings” were shown to perform better, i.e., have better drying potential, than traditional “concealed barrier” systems. (See Definitions below). Ventilated claddings are constructed with an air cavity behind exterior cladding, usually ¾-inch deep as in this study, similar to the cavity created behind a brick veneer. The air cavity is open, ventilated to the outside at the top and bottom of each building story to facilitate air flow behind the cladding, which improves the ability of a wall to dry to the outside.

Ventilated assemblies are typically more complex than concealed barrier systems and require thoughtful and close attention to detail during design and construction. Other considerations include whether the air cavity affects the fire-resistance rating of the wall assembly, and integration with other building components such as windows, doors, vents and similar envelope penetrations.
- **Effect of Interior Humidity:** In the Seattle climate, it is important to maintain average indoor relative humidity (RH) below 60%. This limits the amount of interior moisture available to accumulate in exterior walls. Keeping interior RH within a healthy range (30-60%) also allows walls to dry to the inside when drying to the outside is not possible, provided vapor permeable wall components are used. For most homes and apartments with good ventilation systems, maintaining RH within a healthy range is not difficult. If necessary, other means of dehumidifying may be used—for example, pressurizing corridors with dehumidified air to infiltrate living units or installing dehumidifiers. See discussion below on Choice of Vapor Control Strategy on Interior Side of Wall.
- **Choice of Vapor Control Strategy on Interior Side of Wall:** If RH is generally maintained at less than 60%, the computer modeling showed that more semi-permeable vapor retarding materials are preferable, i.e. materials with a permeability between 1 and 10 perms, e.g. latex primer and paint. If RH is maintained above 60%, the modeling indicates that more vapor control is needed, i.e. materials with vapor permeability around 1 perm, e.g., vapor retarding primer and latex paint, or kraft-faced batt insulation.¹ If RH is maintained higher than 75%, the modeling indicates that a vapor barrier would be required, i.e. materials with a permeability around 0.1 perm or less, e.g., 6- or 4-mil poly.
- **Effect of Mechanical Ventilation:** The net effect of mechanical ventilation, in combination with wind and stack effects, causes periods of air infiltration and exfiltration. The computer modeling predicted a net increase in the moisture load on a south-facing exterior wall. However, the study showed that vapor semi-permeable assemblies were generally able to manage the additional moisture load, i.e., these assemblies were able to store and release moisture as needed, provided interior RH generally remained below 60%.²
- **Effects of Energy Code Requirements:** In the Seattle climate, the modeling showed that increasing the R-

¹Consult the Northwest Wall and Ceiling Bureau for recommendations on use of vapor retarding primers.

² A good air barrier system alleviates most of these effects, as does good air sealing and building compartmentation strategies. The Washington State Energy Code currently requires air leakage to be minimized, but lacks measurable performance requirements. More research on the effects of wind, stack, and mechanical pressures are needed to better understand how these variables affect wall performance.

value of batt insulation marginally affects vapor diffusion, causing increased moisture accumulation in vapor tight walls. In vapor open assemblies, increasing the R-value of insulation has a negligible effect on moisture accumulation.

- **Plywood vs. Oriented Strand Board (OSB):** The study showed that plywood generally performed better than OSB, though the difference in performance was not great.³ The difference between plywood and oriented strand board is smaller when a vapor tight assembly is used in the interior face of the wall because moisture loading from interior sources is reduced. However, performance differences favoring plywood are greater in a vapor open assembly because the more vapor permeable plywood can dry to the inside or the outside as needed. In a vapor open assembly, OSB tends to retain moisture due to its low vapor permeability and the relatively large amount of moisture-wicking end-grain exposed compared to plywood. Vapor open assemblies

are preferred in the Seattle climate, subject to consideration of prevailing interior environmental conditions (see discussion above on [Effect of Interior Humidity](#)).

Another difference between plywood and OSB that was not included in the modeling, but which should be considered when using either product, is the different expansion and contraction behaviors each exhibits when subjected to repeated wetting and drying cycles. OSB tends to remain in an expanded state after drying, while plywood usually returns to its original dimensions.

- **Pre-1984 vs. Post-1984:** Pre-1984 2'x4' walls exhibited better drying that can be attributed to a number of differences. One such difference is the gypsum sheathing board typically used in pre-1984 assemblies provides added resistance to thermal flow and moisture storage, and less resistance to vapor flow. Other differences include lower R-value insulation, use of more vapor permeable stucco formulations, and use of wood frame window assemblies.

How the results of the study might be used

Following are two examples of how results from the moisture study could be used to choose building envelope components, assuming good construction:

Example 1: Normal interior environment:

Under normal interior temperature and RH conditions (below 60%), the hygrothermal modeling suggests that a vapor open wall assembly should perform well, allowing the wall to dry to the outside or inside as needed during the year. Such walls should be capable of managing a small amount of moisture intrusion.

• **Exterior Cladding and Weather Resistive Barrier:**

Ventilated claddings or concealed barrier systems should work well. Two layers of weather resistive barrier should be used to improve drainage.

- **Sheathing:** Plywood (or plywood and gypsum sheathing board if fire-resistive rating is required) is recommended for their semi-permeable vapor transport characteristics. Oriented strand board is an acceptable substitute for plywood, but the wall assembly must be designed to take into account the particular OSB's unique hygrothermal profile and typically low vapor permeability.

³ The hygrothermal performance values used in the study for plywood and OSB were taken from samples previously tested by the Oak Ridge National Laboratory, but do not necessarily represent all types of plywood or OSB. The performance characteristics of engineered wood products are often deliberately varied depending on the types of wood and binders (glues) used, and intended uses of the product.

- **Insulation and Interior Finishes:** Unfaced or kraft-faced batt insulation is recommended, along with gypsum wall board, and at least 2 layers of vapor semi-permeable latex primer and paint.⁴

Example 2: High interior relative humidity conditions:

Under high interior RH and normal temperature conditions, the hygrothermal modeling suggests that for the Seattle climate, a vapor barrier of 1 perm or less, depending on average interior relative humidity, should be installed toward the interior of the wall assembly. Because the high RH prevents drying to the interior, the wall needs to dry to the outside most of the year and be capable of storing some moisture without negative effects during parts of the year. Such walls should also be capable of managing a small amount of moisture intrusion from the exterior.

- **Exterior Cladding and Weather Resistive Barrier:** The computer modeling suggests using a ventilated exterior cladding with a ¾" air cavity to facilitate air movement behind the cladding to keep the wall dry. Two layers of a well-constructed weather resistive barrier should be used to provide additional protection.

- **Sheathing:** Plywood (or plywood and gypsum sheathing board if fire-resistive rating is required) is recommended for its vapor transport characteristics. Oriented strand board is an acceptable substitute for plywood, but the wall assembly must be designed to take into account the particular OSB's unique hygrothermal profile and typically low vapor permeability.

- **Insulation and Interior Finishes:** The computer modeling suggests that under high interior RH conditions, a vapor retarder should be used on the inside face of the wall to limit vapor diffusion into the wall. Well-sealed kraft-faced batt insulation, unfaced batts with poly vapor barrier, or use of a PVA primer is recommended.
- **Interior Environmental Control:** In some cases, it may be more practical to modify interior environmental conditions than to modify wall construction, especially in retrofit applications. Consider adding humidity control to unit or corridor ventilation systems and using waste heat from dehumidification to pre-heat incoming ventilation air when necessary.

⁴ The Washington State Energy Code currently requires vapor retarders to be installed on the warm side (in winter) of insulation. A vapor retarder is defined as a low moisture transmissivity material (not more than 1.0 perm dry cup). Kraft-faced batt insulation meets the WSEC vapor retarder requirement while providing increased vapor permeability under wet conditions when increased drying potential is needed.

Attachment 1

CCAB raises issue of moisture damaged buildings

In 1998, members of Seattle's Construction Codes Advisory Board (CCAB) approached the Department of Design, Construction and Land Use (DCLU) with reports of multifamily building envelopes with significant damage caused by rotting. The damage caused to multifamily housing developments by moisture intrusion fell below DCLU's radar because building permits to replace exterior cladding require only minor review and in many cases no permit is required. While all buildings experience decay that needs repair over time, CCAB members noted that the buildings they were repairing were "young," some less than a year old, most less than 15 years old. CCAB members hypothesized that air tightness and air pressure differences due to energy and ventilation code requirements were partly to blame for the moisture damage problems because these requirements do not let walls "breathe" as they did before these codes were enacted. CCAB asked DCLU to research the extent that energy and ventilation code changes since 1984 contributed to the premature failure of many newer multifamily residential buildings.

Informal Survey Made

To find out more about the extent and causes of the reported moisture damage problems, DCLU undertook an informal survey of a range of multifamily buildings. The survey asked building owners if their building had leaks; if so, where did leaks occur; and an estimate of the construction cost to fix the leaks and resulting moisture damage. All 51 of the buildings in the survey that were built after 1984 reported leaks. The construction cost to fix the 51 buildings built between 1984 and 1998 approached \$100 million, not including fees for attorneys, investigations, designs, and relocation during construction.

The survey confirmed what many area building envelope repair specialists already knew – the main cause of moisture damage stems from water intrusion through interface details, i.e., building envelope penetrations at decks, windows, and doors. In Seattle's mild, damp climate, it doesn't take long for decay fungi to begin rotting out portions of exterior walls that are not protected from repeated wetting without sufficient time or means for drying. Upon investigation of structures with moisture damage, investigators commonly found that flashing and weather resistive barriers did not exist, or if they did exist they were not integrated or installed properly. The lack of a functional weather resistive barrier exposes the interior portions of exterior walls to more

moisture than the components of the wall can safely store and release, which in turn leads to mold growth and eventually rot caused by decay fungi.

Findings from the Seattle moisture damage survey correlated well with data from a more in-depth 1996 study of 37 buildings in Vancouver, British Columbia. The main conclusion drawn from both the Seattle and Vancouver studies is that the primary source of moisture intrusion leading to damage was exterior water entry through interface details. The Vancouver and Seattle surveys confirmed the importance of keeping water out of building envelopes, and that attention needs to be focused on the design and execution of interface details during construction. However, the surveys did not directly address the possible effects of energy and ventilation codes on the performance of building envelopes.

Changes in Codes and Building Materials a Concern

In recent years energy and ventilation code requirements have altered how walls built today transfer heat, air and moisture as compared to walls built as little as 20 years ago. These code changes have required improved thermal performance and added provisions for mechanical ventilation, which have affected the transfer of heat, air and moisture in building envelopes. In addition, the evolution of building products has affected how building envelopes perform with regard to the transfer of heat, air and moisture. In April 1999, DCLU learned of research currently underway at the Oak Ridge National Laboratory's Building Technology Center that aims to increase the understanding of how individual code changes, and changes in building products and practices, affect the hygrothermal performance of walls.

Call for Hygrothermal Performance Analysis

Recognizing that the building industry needs the ability to evaluate how changes in code requirements and building products affect building envelope performance, researchers at the Oak Ridge National Laboratory (ORNL) developed a computer model, MOISTURE EXPERT 1.0. This model simulates the hygrothermal performance of whole wall systems and subsystems using the material property characteristics of each wall component. Hygrothermal performance is the measure of the combined heat, air and moisture flows within a wall system based on the material property characteristics of each component within the wall and the interior and exterior environmental conditions to which the wall will be exposed.

Attachment 2

Definitions

Concealed Barrier Systems are the most common types of exterior walls constructed. In these types of walls, the exterior cladding is the primary weather resistive barrier and is typically installed directly on top of and in contact with a secondary weather resistive barrier. Exterior cladding can be of any type, e.g. stucco, brick, cedar shakes, vinyl, etc. The most common types of secondary weather resistive barriers are “building paper” or “housewrap”, though other materials may also be used. Small channels are typically created between the cladding and secondary barrier by virtue of the imperfect nature of the materials used and varying installation practices. These channels are the primary mechanism by which water that collects on the secondary weather resistive barrier drains out through weep holes or screens installed at the base of the exterior cladding.

Hygrothermal performance is the measure of the combined heat, air and moisture flows within a wall system based on the material property characteristics of each component within the wall and the interior and exterior environmental conditions to which the wall will be exposed.

Perm is a measure of the vapor permeability of a material. A perm rating measures the amount of water vapor that passes through a given area of material over a defined period of time. Perm measurements are taken under “dry cup” or “wet cup” conditions at a constant temperature. Dry cup perm measurements are taken under low relative humidity conditions, less than 50% RH. Wet cup perm measurements are taken under high humidity conditions, 50% RH and above. Some materials have different perm ratings under dry cup and wet cup conditions that are caused by changes in physical properties related to the presence of water in the material. A low perm rating means less moisture passes through a material.

Vapor Barrier, Vapor Retarder, and Vapor Permeable refer to the relative ease with which water vapor can pass through a material. A vapor barrier material, also called vapor impermeable or vapor tight, allows little to no moisture vapor to pass through it. Materials rated at 1 perm or less are considered vapor barriers, e.g.

polyethylene sheet, oil-based paints, and foil-faced insulation sheathings. A vapor retarder material, also called vapor semi-permeable, allows vapor to slowly pass through it. Materials rated at 10 perms or less are considered vapor retarders, e.g. most kraft-faced batt insulation, plywood, OSB, and most latex paints. A vapor permeable material, also called vapor open or breathable, allows moisture vapor to rapidly or freely pass through. Materials rated at more than 10 perms are considered vapor permeable, e.g. most housewraps, building papers, and unpainted stucco and plaster.

Rain Screen Exterior Cladding refers to a design strategy whereby a cavity is created between the exterior cladding material and the secondary weather resistive barrier. The cavity is wide enough to break the surface tension of water and allow incidental water entering the wall system to drain by gravity with the aid of flashings.

Stack Effect and Wind Effect refers to the positive and negative air pressures resulting from the buoyancy of warm air rising through a building and wind blowing on and around a building. Stack effect is caused by a continuous cycle of air rising through a building that tends to create negative air pressures in lower stories of buildings and positive air pressures at the upper stories. As cold outdoor air infiltrates the lower stories of a building, it warms and rises, drawing in new cold air to continue the cycle. Wind effect creates negative pressures on the windward sides of a building and positive pressures on the leeward sides. As used in this definition, positive pressure refers to high interior air pressure relative to outdoor air pressure causing air to migrate from inside a building to the outside. Negative pressure refers to lower interior air pressure relative to outdoor air pressure causing air to infiltrate into a building.

Ventilated Exterior Cladding is a rain screen cladding with openings at the top and bottom of the exterior cladding, typically at each floor, to facilitate the movement of air behind the exterior cladding. The movement of air behind the exterior cladding dries out incidental water that penetrates the rain screen cavity from the outside and drives away moisture vapor that may migrate into the cavity from inside the building.

